Broadband Ground Motion Simulation of the 2010-2011 Canterbury Earthquake Sequence

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ABSTRACT: In this paper, we perform hybrid broadband (0-10 Hz) ground motion simulations for the ten most significant events (M_w 4.7-7.1) in the 2010-2011 Canterbury earthquake sequence. Taking advantage of having repeated recordings at same stations, we validate our simulations using both recordings and an empirically-developed ground motion prediction equation (GMPE). The simulation clearly captures the sedimentary basin amplification and the rupture directivity effects. Quantitative comparisons of the simulations with both recordings and the GMPE, as well as analyses of the total residuals (indicating model bias) show that simulations perform better than the empirical GMPE, especially for long period. To scrutinize the ground motion variability, we partitioned the total residuals into different components. The total residual appears to be unbiased, and the use of a 3D velocity structure reduces the long period systematic bias particularly for stations located close to the Banks Peninsula volcanic area.

1 INTRODUCTION

Ground motion prediction is of great importance for structural and geotechnical engineers to design earthquake-resistant structures. Conventionally, ground motion prediction is obtained from empirical ground motion prediction equations (GMPE) (Boore and Atkinson 2008, Campbell and Bozorgnia 2008, Chiou and Youngs 2008, Spudich et al. 1999) that are developed based on historically recorded ground motions worldwide. This empirical approach has the benefit of being computationally expedient, however, it has multiple limitations, including: the limited range of magnitude and source-to-site distances that the models are well constrained for; and the fact that they provide only ground motion intensity measures (e.g., peak ground acceleration (PGA), peak ground velocity (PGV), spectral acceleration (SA) at different vibration periods), and not acceleration time series that are directly needed for non-linear response history analyses. Over the last few decades, there have been considerable efforts to develop realistic ground-motion simulation techniques which overcome the deficiencies of GMPEs. These techniques can be classified into three major categories: (1) 'deterministic' or 'physics-based' approaches (Olsen et al. 2009, Olsen et al. 2006) that incorporate the underlying seismological and geological information to specify the complexity of the seismic source and structure of the Earth's crust (which due to computational and knowledge constraints is limited to lower frequencies); (2) simplified 'stochastic' approaches (Boore 2003, Yamamoto and Baker 2013) that are based on semi-empirical models with few physical parameters; and (3) so-called 'hybrid' approaches (Graves and Pitarka 2010, Liu et al. 2006, Mai et al. 2010) which combine the first two approaches at low and high frequencies, respectively. In the present study, we adopt the hybrid approach to simulate strong ground motions from the 2010-2011 Canterbury earthquakes, covering the entire frequency range of interest to engineers (i.e. frequencies from f=0-10 Hz, enabling response spectra from *T*=0-20+ seconds).

Although significant progress has been made in developing physics-based numerical simulations to predict ground motion, verification and validation of such simulation techniques are essential to ensure their robustness and reliability for engineering use. The Southern California Earthquake Center Broadband Platform (SCEC BP), for instance, has been initiated to validate the existing simulation techniques and the ground motion metrics rigorously (Goulet et al. 2015). One way to evaluate the simulation result is by comparing the simulated ground motion parameters with GMPEs (Mena et al. 2010) or by reproducing the characteristics of the recorded ground motion from past earthquakes. For instance, Graves and Pitarka (2010) simulated the Loma Prieta earthquake to validate their hybrid approach. Likewise, Ramirez-Guzman et al. (2015) tested three hybrid ground motion simulation codes for the 1811-1812 New Madrid Earthquakes. The 2010-2011 Canterbury earthquake sequence also provided a wealth of ground motion data, which provides an opportunity to validate ground motion simulations, but also to examine the complexity of these events. This earthquake sequence is characterized by complex ground motion which is partially due to intricate source processes and geological structures in the area. Various studies have examined observed data and investigated this complexity (Bradley 2015, Bradley and Cubrinovski 2011, Fry et al. 2011). However, in most of these previous studies, the characteristics of the ground motion are compared with empirical ground motion models. The aforementioned shortcomings of this empirical approach motivate the use of physics-based methods to analyze further the Canterbury earthquake sequence.

This study investigates the role of 1D/3D crustal structure and rupture model variability on ground motion simulation. The simulations are carried out using a hybrid approach for ten most significant events in the 2010-2011 Canterbury earthquake sequence. Here, we use both the recordings from the earthquake sequence and a New Zealand-specific GMPE to validate the simulation results.

2 ADOPTED HYBRID GROUND MOTION SIMULATION METHOD

We use the hybrid ground motion simulation approach of Graves and Pitarka (2010, 2015), which computes the low- and high-frequency wavefields separately, then combines the two motions to form broadband seismograms. The chosen transition frequency is 1Hz, up to which the low-frequency part is well resolved. At low frequencies (f<1Hz herein), the principal features of strong ground motions are modeled by solving a 3D heterogeneous viscoelastic wave propagation problem based on a staggered-grid finite difference scheme with fourth-order spatial and second-order temporal accuracies. This approach requires rigorous representations of the source and the wave propagation effect. We utilize a kinematic rupture model to represent the source and both 1D and 3D velocity models for the crustal structure. Anelastic attenuation is incorporated in terms of material quality factor Q, using empirical relations $Q_S=50\ Vs$ and $Q_P=2Q_S$. To achieve realistic ground motion up to 1Hz, we consider a minimum shear wave velocity of Vs=500 m/s and a spatial grid spacing of h=0.1km. At high frequencies (f>1Hz), the ground motion simulation is based on a semi-empirical ray-based approach. It considers a stochastic source radiation pattern and simplified wave propagation scattering through a 1D layered approximation of the 3D model, with high-frequency attenuation factor, κ=0.045 and a mean Brune stress drop parameter of $\Delta\sigma$=5MPa. These values are typical for active shallow crustal regions (Graves and Pitarka 2010), as demonstrated by source-specific studies of the Canterbury earthquake sequence (Oth and Kaiser 2014). Near-surface site response is incorporated following the simplified frequency- and amplitude-dependent site correction factors of Campbell and Bozorgnia (2014).

To examine the importance of 3D velocity model in ground motion simulation, we consider two velocity structures for the Canterbury area (Lee et al. 2015). The first model (v1.02) is a 1D velocity structure composed of homogeneous horizontal layers. The second crustal model (v1.64) is a 3D velocity model derived based on travel time tomography, seismic reflection, petroleum and hydrologic wells, active and passive surface wave analysis, and seismic cone penetration tests.

An adequate source representation also plays a fundamental role in ground motion prediction studies. Finite fault models were adopted for the four events with magnitude $M_w \geq 5.9$ (4/09/10, 22/02/11, 13/06/11, and 23/12/11) and point sources for the remaining smaller events. The fault geometry is adopted from available slip models for the events (Beavan et al. 2011, Beavan et al. 2012, Beavan et al. 2010). However, the spatiotemporal evolutions of the rupture from such prior studies (if available) are not themselves utilized. Instead, they are generated using stochastic slip generators (Graves and Pitarka 2015, Mai and Beroza 2002).

3 SIMULATION RESULTS

3.1 Spatial and temporal variation in ground motion velocity

Figure 1 depicts time snapshots of the simulated seismic wave propagation in the 3D heterogeneous crustal structure for the two most devastating events during the Canterbury earthquake sequence, the M_w7.1 Darfield and M_w6.2 Christchurch events. The depicted velocity values represent the absolute maximum from the three components velocity at different time. These snapshots illustrate the influence of the source and the underlying geological feature of the area. For the M_w6.2 event, ground motions intensify as they propagate towards the north-west. This feature is mostly associated with the amplification of the seismic waves, as they encounter the sedimentary basin in the north of Christchurch (shown as a dark grey area, Fig. 1). At station REHS, located in the sedimentary basin, for instance, the peak ground velocity (PGV) is about 57 cm/s, compared with a PGV of 11 cm/s at the station MQZ, located in Banks Peninsula volcanic rock (south-eastern part). The figure also illustrates the wavefield crossing the volcanic rock in the Banks Peninsula has a smaller amplitude compared with the waves propagating further north in the Canterbury plain. This is presumably due to the presence of volcanic rock that scatters and reflects the incident wavefield. Similar ground motion amplification effects in the sedimentary basins are also observed for all the other events. For the M_w7.1 Darfield earthquake, these effects are combined with significant fault directivity. Videos of these simulations are available at https://sites.google.com/site/brendonabradley/videos

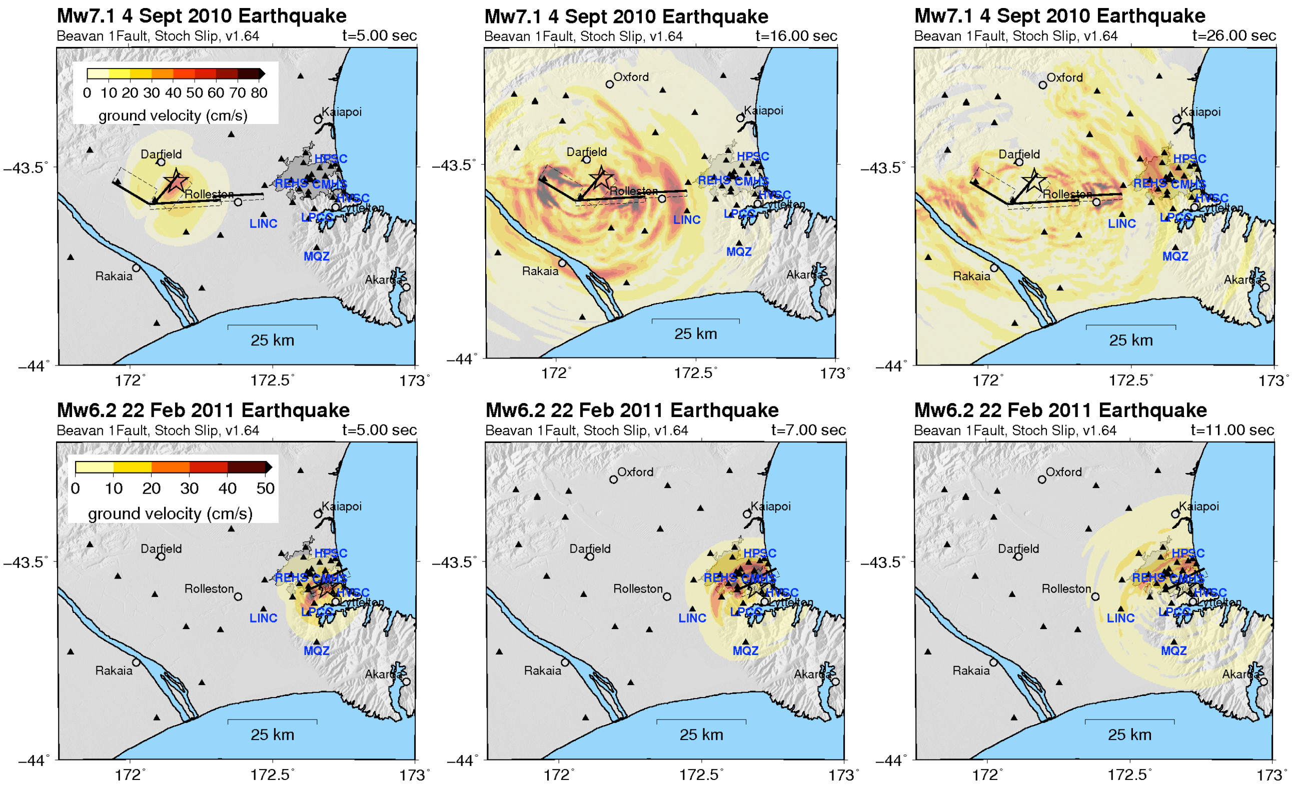

Figure 1: *Velocity snapshots for the* M_w 7.1 *Darfield (top row) and* M_w *6.2 Christchurch (bottom row) events. Snapshots are taken at 5, 16, 26s for Darfield event and 5, 7, 11s for the Christchurch event.*

3.2 Quantitative comparison with observations and GMPE

To validate the simulation results, Figure 2 compares the observed and simulated peak ground acceleration (PGA), and 5% damped pseudo-spectral acceleration (SA) for three events (4 September 2010, 26 December 2010, and 22 February 2011), the 26 December event being an example of a smaller point-source event. The metrics are computed for the geometric mean of the two horizontal components. It can be seen that the PGA and SA values of the simulated ground motions match the observations reasonably well. The simulations also reproduce the overall distance attenuation trends from the empirical GMPE of Bradley (2013). Despite these general consistencies, it is important to note that in several instances, the observed ground motion amplitudes depart from the general GMPE trend. These stations are mostly located in the sedimentary basin, and such departures from the GMPE are well captured by the simulation at long periods, particularly for the large magnitude events.

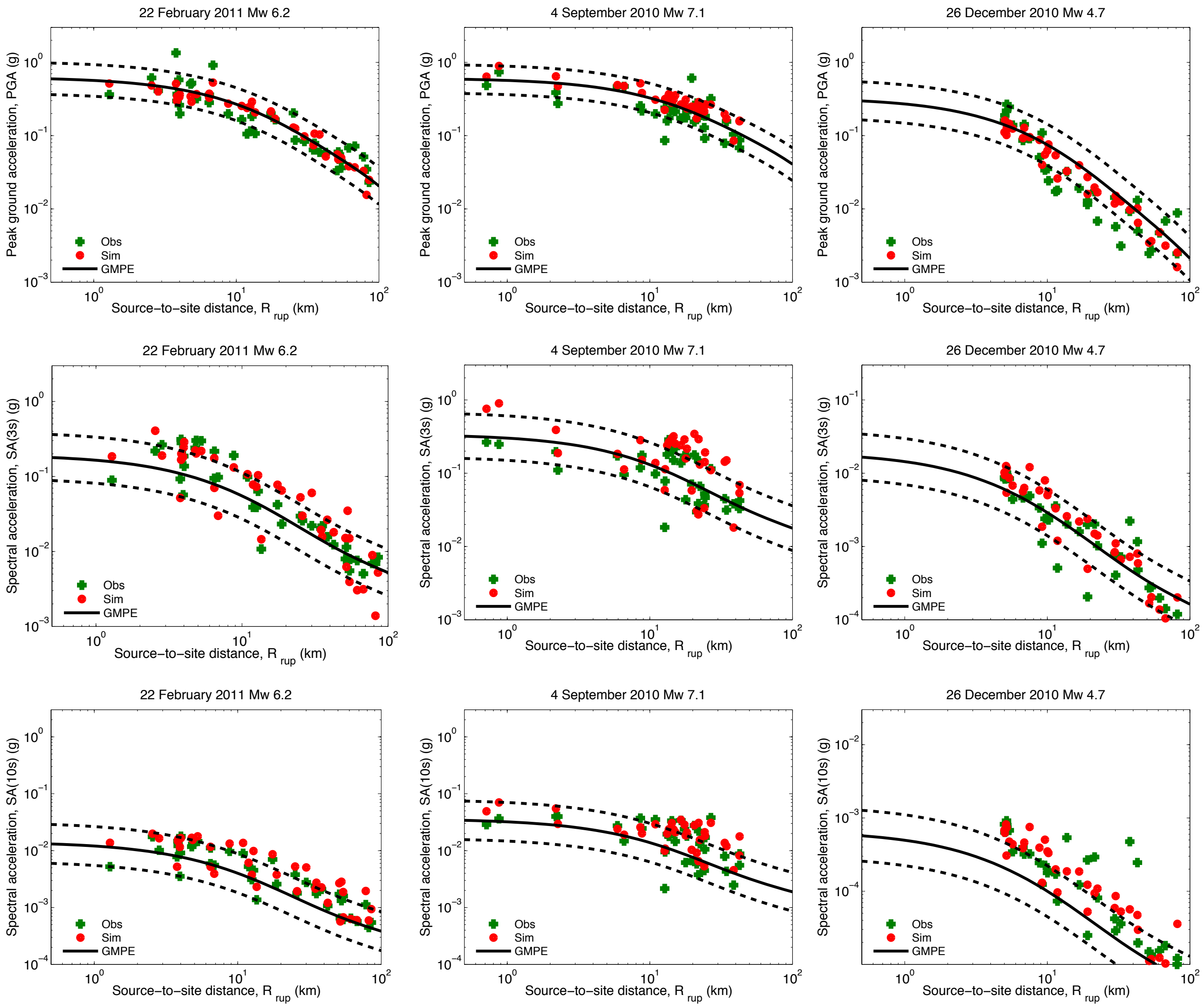

Figure 2: *Intensity measure (Peak ground acceleration and Long-period (T=3, 10s) pseudo-acceleration response spectral amplitude) comparison of the simulated, observed, and empirical ground motion for Feb 22,2011 Sept 4, 2010 and Dec 26, 2010. Note the different axis scaling.*

To further assess the quality of the broadband simulation, statistical properties (specifically the mean and standard deviation) of the residuals are analyzed. The residual is computed as the difference between the logarithm of the observed and simulated intensity at each station (i.e. residual=*ln*(obs/sim)). Figure 3 illustrates the distribution of the residuals across all stations at different vibration periods for the three events presented in Figure 2. The incorporation of the source and 3D velocity model complexity in the simulations clearly reduces the long period bias compared with the prediction from the empirical GMPE (Bradley and Cubrinovski 2011). Moreover, an improvement of the fit is observed using 3D-crustal structure over the 1D structure, particularly at long periods. It is important to note that the high frequency (short period) methodology uses only the 1D velocity structure, and the parameters (e.g., stress drop $\Delta\sigma$=5MPa) are constant for all ten events (and not manipulated for each event). To analyze the contribution of each single station, we partition the residual into between-event and within-event components.

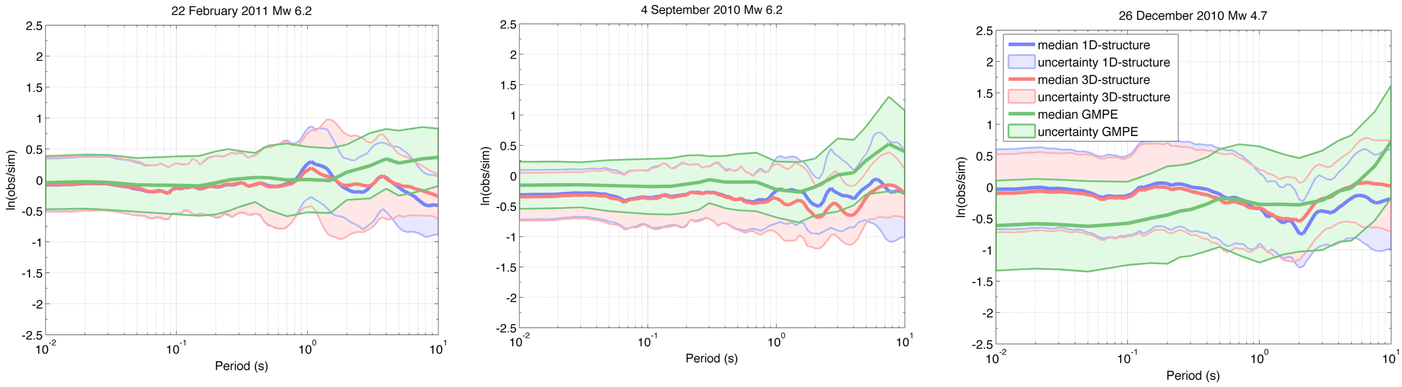

Figure 3: *Distribution of the prediction-observation residuals from simulations and empirical GMPE. Total bias from 1D-velocity structure (blue), 3D-velocity structure (red), and GMPE (green) for Feb 22,2011 Sept 4, 2010 and Dec 26, 2010 events.*

3.3 Examination of systematic bias at specific stations

Since the ten events with magnitude $M_w \geq 4.7$ of the earthquake sequence are well recorded by a similar set of strong motion stations, it is possible to identify from the simulation the presence of systematic site response at individual stations, and also to analyze the ground motion uncertainty. Figure 4 shows the total and between-event residuals of SA for the ten events considered. The total mean residual oscillates around zero model-bias. Since the total residual combines the variabilities among events (magnitude, depth, faulting) and sites, it can be partitioned into between-event and within-event residuals. The between-event residuals (shown in pink, Fig. 4) reveal no apparent trend with the event magnitude and contribute about 50% of the variability. We also examine the SA residuals for the ten events at individual stations using 1D and 3D crustal structures (Fig. 5). For all four stations illustrated, the use of 3D velocity model shows less bias at long-period (T>1s) compared with 1D velocity model-based simulations. The improvement is significant particularly at stations CMHS, LPCC, and HVSC located close to the Bank Peninsula volcanic area. Thus, while there is not a large difference between the long-period simulation prediction based on the 1D and 3D velocity models in an average sense across all 10 events (Fig. 3), the results of Figure 5 illustrate that this is partially the result of subtractive cancellation, meaning that the averaging of SA residuals hides some features observed at individual stations and that the station-by-station biases clearly illustrate the improvement of the 3D velocity model.

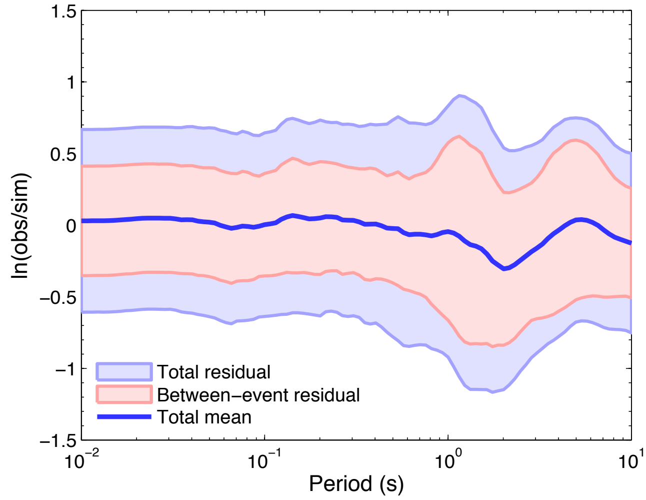

Figure 4: *Ground motion between-event and total residuals for the 10 major events during the Canterbury earthquake sequence.*

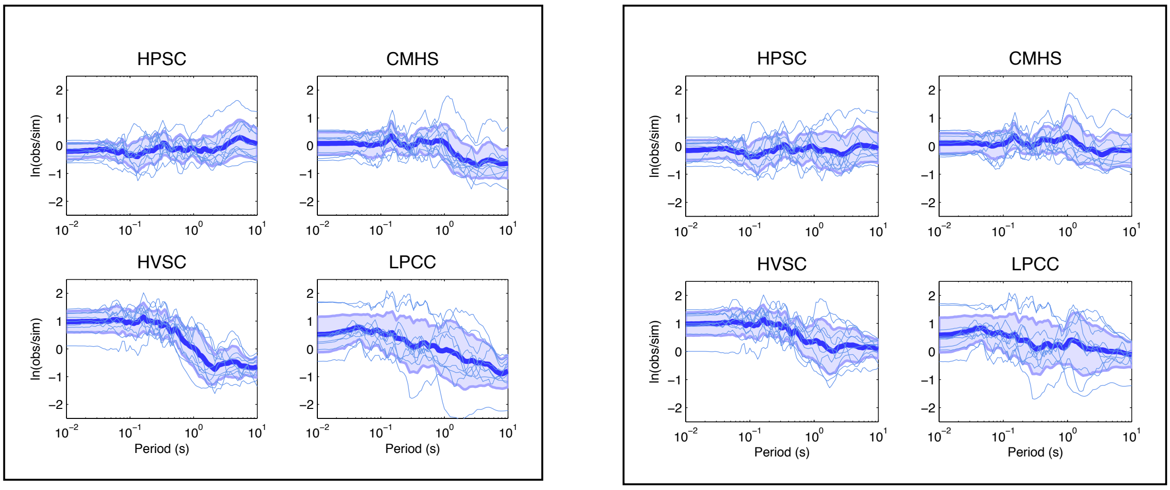

Figure 5: *Systematic site effects at individual stations for major 10 events: 1D (left panel); 3D-velocity models (right panel). Residuals for individual events are shown in thin lines, with the mean shown in the thicker line and the 16th and 84th percentile range shown as a filled area. The reduction in the bias at long periods (T>1s) due to the incorporation of the 3D velocity model should be noted.*

Despite the comments in the previous paragraph, it should be noted that the simulated motions still exhibit systematic biases at shorter vibration periods (e.g., average residuals of approximately one for short periods at the HVSC station). Jeong and Bradley (2015) illustrated that explicitly modeling the detailed near-surface stratigraphy and topography (rather than the simplified Vs30-based site response adopted in the present study) can effectively remove the short-period bias seen for the HVSC station. Thus, apparently a more realistic treatment of near-surface site response across all stations is likely to improve the ground motion prediction at short periods, and is the focus of on-going work.

3.4 **Effect of rupture model variability**

In addition to the uncertainties in the velocity structure and site response model, there is also uncertainty in the source rupture model, which is generated using a stochastic random-field as noted earlier. This section presents an example of the effect of rupture model variability on ground motion by considering ten rupture realizations for the M_w 6.2 Christchurch earthquake. These realizations vary in terms of the locations of high- and low-slip locations (few kilometers differences since the fault size is 16x9km) The distribution of the SA residuals (Fig. 6) from each of the resulting ten ground motion simulations illustrate that the effect of rupture model variability does not have a strong vibration period dependency. It also reveals that the effect of rupture model variability is relatively small – about 10% of the total ground-motion uncertainty. However, it is important to note that slip distribution uncertainty is only one component of the total source uncertainty (which includes hypocentre location, fault geometry and dimensions).

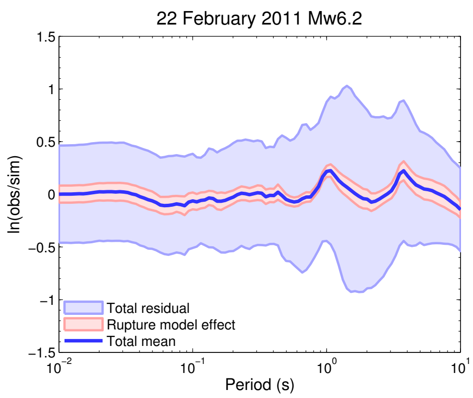

Figure 6: *Total residual for 10 realizations for the M_w 6.2 Christchurch event with the effect of random realization of the slip model on the variation in the mean of the residuals.*

4 CONCLUSIONS

This paper presents hybrid ground motion simulations for the 2010-2011 Canterbury earthquake sequence. The simulations were performed using both 1D and 3D crustal structure models to examine the role of 3D basin conditions. The simulation results were validated directly against the ground motion observations and also empirical GMPEs. They suggest that the crustal structure is a key contributor to the variability of simulated ground motion, particularly in the low-frequency range. The use of 3D-velocity structure captures the structural complexity of sedimentary basin and yields a better prediction of the observations compared with those from the 1D-velocity model. While the ground motion simulations have several clear areas for further improvement (regarding source and site-effects modelling), already the simulations provide equal or better predictions of the observed ground motion amplitudes compared to that of the empirical GMPE over the considered range of vibration periods.

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